REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	27 February 1995	Final Technical Report 7/14/94-2/28/95

4. TITLE AND SUBTITLE

Medical Trauma Assessment Through the Use of Smart Textiles

5. FUNDING NUMBERS

DAAH01-94-C-R190

6. AUTHOR(S)

Michael L. Burns

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Science, Math & Engineering, Inc.
45 Manning Road
Billerica, MA 01821-3934

8. PERFORMING ORGANIZATION REPORT NUMBER

SME RR-1

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Advanced Research Projects Agency
DIRO
3701 North Fairfax Drive
Arlington, VA 22203-1714

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either express or implied, of the Advanced Research Projects Agency or the U.S. Government

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Survival rates at military and civilian trauma sites decrease dramatically if medical treatment is delayed for more than the golden hour. Remote gathering of advance wound information is possible with *medical smart textile*, an innovation by Science, Math & Engineering, Inc. Medical smart textile is an electrically conductive fabric possessing a cross hatched network of conducting paths etched into the textile. Open wound information would register in the textile as holes resulting from penetrating projectiles breaching the fabric. Interrogation for open wound information could occur passively, as a wear-and-forget fabric, or actively, as a wear-and-activate fabric. The passive mode of the textile is remotely interrogated by a radar for wound holes whereas the active mode of the textile senses wound holes as changes in conductor network resistance. Detection of holes by radar in the passive mode was successfully demonstrated at the MIT Lincoln Laboratory indoor radar range.

14. SUBJECT TERMS

Smart textiles; wound information; electrically conductive fabrics; radar; camouflage; medical trauma; remote sensing

15. NUMBER OF PAGES 18

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

SME RR-1

Final Scientific and Technical Report

Reporting Period: 14 July 1994 to 28 February 1995

Medical Trauma Assessment Through the Use of Smart Textiles

27 February 1995

Advanced Research Projects Agency (ARPA)
Defense Small Business Innovation Research Program

ARPA Order No. 5916, Amdt 67
Issued by U.S. Army Missile Commander Under
Contract # DAAH01-94-C-R190
Contract Expiration Date: 28 February 1995

Prepared By:

Dr. Michael L. Burns, Principal Investigator
Science, Math & Engineering, Inc.
45 Manning Road
Billerica, MA 01821-3934
(978) 663-9500 ext. 282

Prepared For:

Defense Technical Information Center
ATTN: DTIC-OMI
8725 John J. Kingman Road, Suite 0944
Fort Belvoir, VA 22060-6218

Table of Contents

1. Phase I TRP Effort

The Advanced Research Projects Agency (ARPA), Advanced Biomedical Technology Program (ABMT), has identified a need for timely medical information at an injury scene or battlefield in support of decisions to manage overall responses to medical trauma. The significance of timely medical information is demonstrated by survival rates that decrease dramatically if treatment is delayed for more than the golden hour. Medical trauma caused by wounds at a military battlefield or a civilian injury scene can be assessed through the use of *medical smart textile*, an innovation proposed by *Science, Math & Engineering, Inc. (SME)* under the TRP ARPA Phase I SBIR. A *smart textile* is a predesigned fabric capable of sensing information about its environment and then communicating that information.

Diagnosing open wounds can be realized by wearing a medical smart textile composed of currently available electrically conductive fabric that has been tailored to relay wound information. Any dedicated uniform such as a military battledress uniform (BDU), a firefighter's uniform or a civilian police uniform containing the smart textile can be interrogated for open wound information; that information manifesting itself as a hole in the smart textile fabric. The use of medical smart textiles would reduce the time needed by trauma site care personnel to communicate wound damage information, freeing them to administer needed medical attention.

A related effort of the ARPA Advanced Biomedical Technology Program is to modify the surgical theater by taking advantage of new materials and sensors that enhance operating procedures. Medical smart textiles support this effort as wide area smart sensor arrays in the form of a fabric. The Surgical Operating Environment of the Future will be capable of collecting physiological data through sensors imbedded in the environment which take the form of medical smart textiles.

2. SME Phase I Technical Motivation

The general objective of the SME Phase I effort was to design a medical smart textile capable of being interrogated for open wound information. Interrogation of the smart textile is non-invasive to the wound and yields the advance wound information needed to speed care to trauma cases. The smart textile, a layer of fabric closest to the skin, can be considered as passive or active. It is this layer of fabric closest to the skin, that when breached, indicates the presence of a wound. The reason for the medical smart textile, passive or active, lying as close as possible to the skin is to prevent the false identification of wounds. If the medical smart textile were to be exposed as an outer layer, holes could be produced, for instance, by snagging the fabric on equipment or trees resulting in the false identification of wounds. Placing the medical layer inside prevents the identification of superficial tears in the fabric as wounds.

Passive and active forms of the smart textile differ primarily in their methods of textile interrogation. The passive version of the smart textile is remotely interrogated by a radar for open wound information while its active counterpart relays its wound information after being interrogated locally by a personal monitor. A specific objective of designing the medical smart textile was to produce a fabric that is wearable, breathable, durable, affordable, launderable, survivable and capable of camouflage. A benefit of the smart textile approach to sensing wound

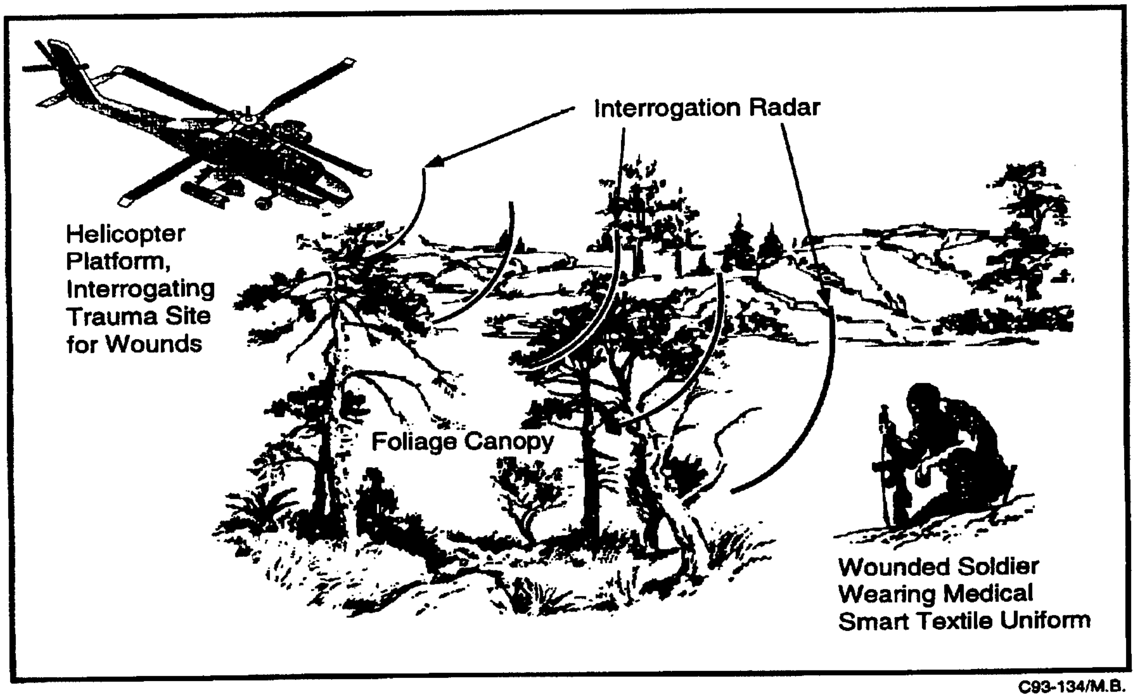


Figure 1 Passive mode of medical smart textile worn by a wounded soldier being interrogated remotely for advance wound information by an illuminating radar.

information is the ability to maintain the existing properties of fabrics that comprise the smart textile. An added benefit of the SME design is the ability to switch easily between active and passive modes of operation. If the medical smart textile were to fail in the active mode, the passive mode could be invoked without any change to the fabric.

The primary focus of the SME Phase I effort was design of the passive mode of the medical smart textile, a wear-and-forget fabric, that does not require any particular activation by the wearer. In the passive mode of the textile, a platform such as a helicopter, that is remotely interrogating the smart textile through radar illumination, must use radiation capable of penetrating obstacles, foliage and outer layers of clothing. This penetration requirement of the radiation is the prime reason for using a radar, as opposed to visible, infrared or thermal radiation, which do not possess the same ability for penetration. The frequency (wavelength) of the radar will determine its penetration capability in addition to its ability to resolve the minimum wound size registered in the smart textile. In order to minimize undesired scattering of the illuminating radar, radar wavelengths larger than obstacles that must be penetrated should be used. Figure 1 illustrates the passive mode of medical smart textile interrogation.

A secondary focus of the SME Phase I effort was design of the active mode of the medical smart textile. The active textile, a wear-and-activate fabric, is composed of the same electrically conductive fabric that comprises the passive textile. The active textile differs from the passive textile by requiring a monitor that reads changes in a resistor network etched into the conductive fabric. Registration of an open wound would result from the change in resistance caused by a projectile breaching the resistor network of the fabric.

3. SME Phase I Technical Results

The SME Phase I effort addressed four technical areas regarding open wound identification through the use of medical smart textiles. Those areas were (1) constraints imposed on the textile by the trauma site; (2) radar interrogation of the textile in a radar test range; (3) desired properties of a field interrogation radar and; (4) relevant design considerations for using smart textiles in the Surgical Operating Environment of the Future.

3.1 Constraints on Sensing Medical Trauma

3.1.1 Competing Radio Frequencies

For military vehicles, communication equipment operates at UHF near 400 MHz (75 cm) while for dismounted soldiers, it operates at VHF between 35-80 MHz (3.75-8.6 m). Frequencies considered in these bands for medical smart textile interrogation should either be avoided or carefully chosen so as not to interfere with existing communication links. In the passive mode of smart textile interrogation, interference with these links is not a problem. Passive textile interrogation occurs at higher frequencies (shorter wavelength), in S-band to attain better resolving power for smaller wounds. The desire for finer wound resolution naturally drives the frequency (wavelength) needed for passive smart textile interrogation to radar bands higher (shorter) than UHF/VHF. The active mode of the smart textile, however, would benefit from the use of longer transmission wavelengths (lower frequencies) in order to overcome environmental clutter when transmitting wound information.

3.1.2 Radar Camouflage

Radar camouflage of medical smart textile can be selectively controlled by reducing the amount of electrical conductor in the textile. In a military setting, if the medical smart textile, operating either in the passive or active mode, is illuminated by an unfriendly radar, it should not be easily observed by that unfriendly radar. The smart textile should return enough signal to a friendly radar to diagnose open wound information but not so much signal to an unfriendly radar so as to create a radar signature large enough to threaten the dismounted soldier. The degree of radar camouflage is determined by the signal-to-clutter ratio [21, 22], that is, the ratio of radar signal from the smart textile to the radar return from surrounding clutter such as rocks and trees. A lower signal-to-clutter ratio means a better radar camouflaged smart textile [4, 5, 16, 17].

$$\frac{S}{C} = \frac{\sigma_{RCS}}{\sigma_{clutter} R \theta_{beam} c \frac{\tau}{2} \sec\phi} \qquad \textbf{Equation (1)}$$

The signal-to-clutter ratio *S/C* is expressed in Equation (1) where

σ_{RCS} = radar cross section of dismounted soldier wearing medical smart textile
$\sigma_{clutter}$ = radar cross section per area of clutter background
R = distance between interrogating radar and smart textile
θ_{beam} = beam width of interrogation radar
c = speed of light

τ = radar pulse width
ϕ = radar look angle at smart textile

A signal-to-clutter ratio of S/C~5 results from characteristic values of σ_{RCS}~3 meter^2 [19], $\sigma_{clutter}$~0.09 meter^2/meter^2 [18]; R~1 kilometer; θ_{beam}~2°, τ~1 ns and ϕ~45° at ~3 GHz (S-band). The signal-to-clutter ratio can be selectively lowered by simply reducing the amount of conductor in the fabric. This results in improved radar camouflage for the medical smart textile. The reduced amount of conductor lowers the fabric conductivity which decreases the radar cross section σ_{RCS}. Wrinkles and creases in the medical smart textile naturally tend to improve radar camouflage by lowering the radar cross section.

3.1.3 Open Wounds

The types of wounds for which medical smart textile was conceived are open wounds resulting from penetrating objects. To categorize, military wounds tend to penetrate the skin leaving an open cavity whereas civilian wounds tend to be blunt, possibly damaging bone, but not as likely to leave an open cavity. Of course, this is not to say there are no civilian open wounds or military blunt wounds however a rough delineation does exist. Characteristic sizes of open wounds and correlation to munitions is described in [24]. Discussions with COL Bellamy of Walter Reed Army Medical Center regarding wounds and Dr. Carroll Peters of the University of Tennessee Space Institute regarding wound simulation have set scales for the size of soft tissue damage both in the permanent cavity and zone of extravasation.

Radar measurements of conductive fabric indicate that holes in the textile, much smaller than those left by a small caliber round, are easily detected. The textile in both the active and passive modes can be read for wound location and size. In the passive mode, the interaction of the traveling wave of the interrogation radar with discontinuities in the conductivity of the fabric, caused by a penetrating object, reveals the size and location of wounds. In the active mode, an object penetrating the resistor network etched into the textile, changes network resistance, thereby revealing the size and location of wounds.

3.1.4 Trauma Site

Active and passive modes of smart textile interrogation must minimize undesired scattering of radiation. Wound information is transmitted by radio in the active mode and interrogated by radar in the passive mode. Trauma sites possess sources of clutter that absorb, scatter and impede radio transmission and radar interrogation. A common feature of the environment effecting the smart textile sensing scenario is the return from background clutter that results from objects other than the smart textile being interrogated. A common clutter source requiring penetration is foliage canopy. Successful penetration of foliage canopy has been demonstrated by using an ultra-wideband synthetic aperture radar [3, 7, 8, 20, 23]. The signal-to-noise ratio determines the power of the illuminating radar while the signal-to-clutter ratio determines the radar camouflage characteristics of the smart textile. Both of these ratios depend on the signal averaging time needed to extract the desired signal level.

While engaging the enemy in a military battle, squads of soldiers attempt to maintain close proximity through bounding or traveling overwatch [9]. Fireteams are spaced ~20 meters apart while members of a fireteam are spaced ~10 meters apart. This form of engagement might suggest some clustered pattern of wounds that could be exploited upon sensing. The experience

of medics however is that there is no particular pattern to military trauma sites. Civilian trauma sites display the same lack of regularity [25]. Sweat, a conducting liquid, needs to be further explored for its effect on sensing wound information in the conductive fabric network.

3.1.5 Health Safety

The biological exposure index (BEI) [1, 13] for illumination by an S-band radar at 3 GHz is 10 mW/cm^2. The BEI is defined as that level of exposure above which health safety is jeopardized. The ratio of transmitted to received power for the passive mode of textile interrogation is estimated at 10^{-6}. To remain below the BEI at the receiver, the maximum transmitted power should not exceed a kilowatt, neglecting detector efficiencies. Including detector efficiencies would increase the maximum power level beyond a kilowatt.

The silver in silvered conductive fabric is antibacterial [12] and would be a health benefit to a trauma victim wearing medical smart textile. Silvered conductive fabric, the second entry in Table 1, was one of the fabrics successfully tested at the indoor radar range.

3.2 Medical Smart Textile

3.2.1 Electrically Conductive Fabric

Active and passive medical smart textiles both require a substrate of electrically conductive fabric. Active medical textile requires a network of conductors that can be read for wound information; the network being formed by a cross hatched grid of conducting paths that have been etched into the fabric. Conducting paths of the network should not exceed a few millimeters in either width or separation, to ensure reasonable wound size resolution and location.

The original SME design concept for the passive textile was to produce a fabric possessing conducting filaments capable of being interrogated by a radar for open wound information. Questions of filament type, placement and conductivity were to be explored. An array of filaments was envisioned that would remain aspect invariant upon different interrogation orientations of the radar. A design for the passive textile, consistent with the original SME constraints, but without the use of filaments, is possible with a piece of uniformly conductive fabric. Uniformly conductive fabric was obtained and successfully tested for the ability of a radar to resolve small holes in them. A piece of active textile possessing conductors in a network spaced on millimeter scales would also appear uniformly conducting to the longer wavelengths used to interrogate the passive textile. This naturally admits the possibility of using the same fabric for both active and passive textile wound identification.

Samples of uniformly conductive fabrics were obtained from Sauquoit Industries, Inc. and tested in the MIT Lincoln Laboratory indoor radar range at X-band. X-band was used to prove the principle of remotely detecting a small caliber wound by a radar. The radar to be used in the field would actually be an S-band system due to the requirement of foliage penetration. Table 1 lists properties of four of the samples measured at the radar range. Sauquoit Industries, Inc. is capable of supplying not just uniformly conductive fabric, but also fabrics containing the conductive network specified by SME to produce the active textile. Figure 2 is a photograph of two electrically conductive fabrics which are listed as the first two entries in Table 1. The fabric on the left is the first entry in Table 1 and the fabric on the right is the second entry.

Table 1 Electrically Conductive Fabrics

Entry	Supplier	Description	Weight (oz/yd^2)
1	Sauquoit - Precision Fabrics	blue; woven 30 denier ripstop; 10 conductive yarns in weft; warp 30 denier nylon	3.6
2	Sauquoit - Prodesco	silver; woven 30 denier ripstop; 10 conductive yarns in warp and weft; 100% conductive yarn	1.4
3	Sauquoit	warp knit 15 denier mesh	1.0
4	NRDEC (Natick)	anti-static; carbon grid; polyester	3.0

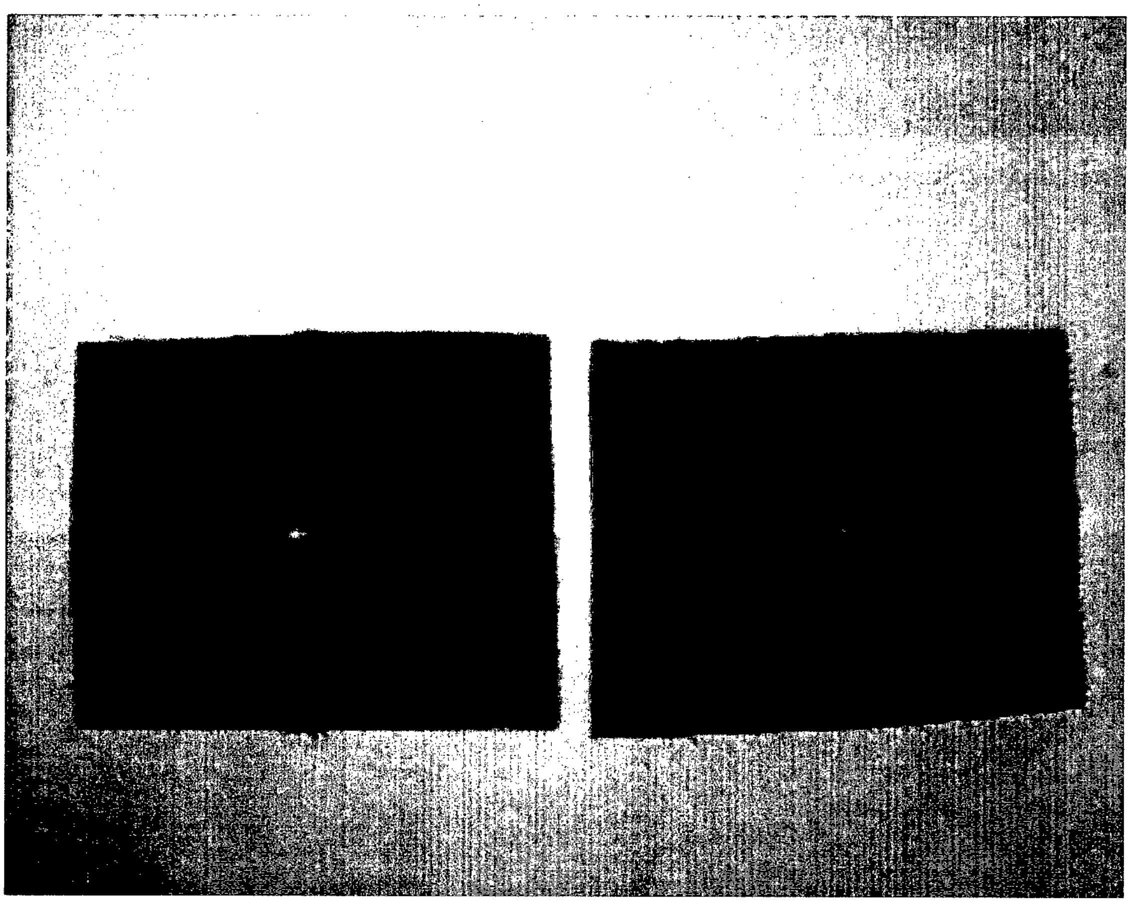


Figure 2 Electrically conductive fabrics tested in the MIT Lincoln Laboratory radar range to determine the ability of a radar to resolve small holes representative of open wounds caused by small caliber rounds (fabrics supplied by Sauquoit Industries, Inc.)

3.2.2 Radar Measurements of Electrically Conductive Fabric

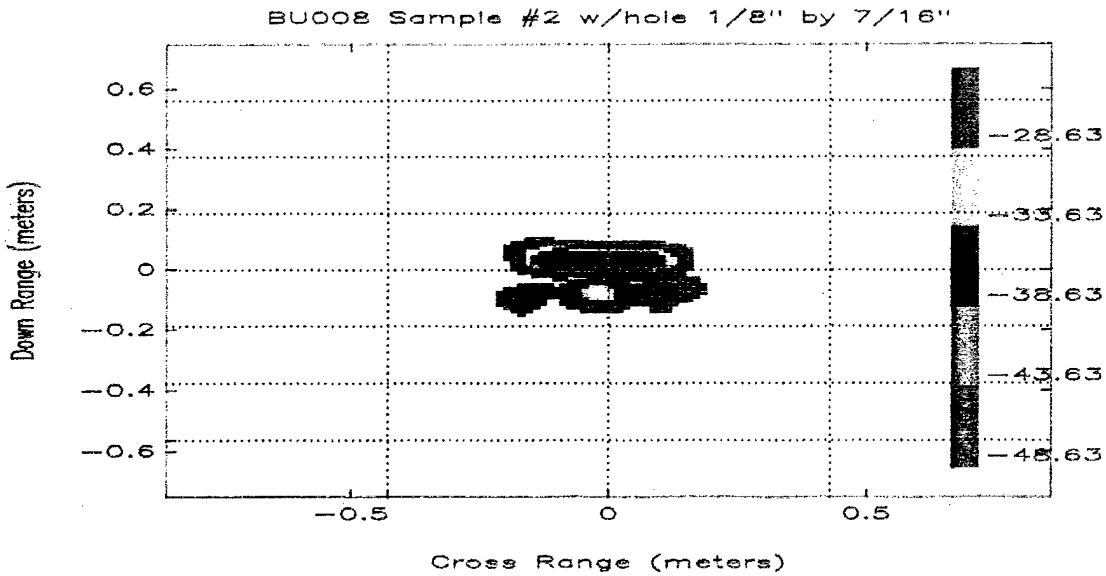
Conductive fabrics could be clearly detected by the interrogation radar. Fabrics of different electrical conductivities were measured to test the ability of a radar to resolve a hole representative of an open wound caused by a small caliber round. Fabrics were first measured for their radar return without a hole. Then a 1/8" x 7/16" rectangular hole was cut in the center of the fabric and measured again. The rectangular fabric samples were 9" x 12" and a 12" x 12" steel plate was used as a reference measurement. An immediate observation was that the 100% conductive fabrics produced as much radar return as the steel plate.

Detection of a hole in a conductive fabric by a radar is clearly demonstrated in Figures 3 and 4. The 1/8" x 7/16" rectangular hole cut at the center of the fabric was representative of a penetrating object that breached the fabric and then caused an open wound. Expressed in munition calibers, the size of the hole is ~3 caliber x 11 caliber. In actually, the interrogation radar detects the edge of the hole, not simply the open area of the hole. The traveling wave of the radar detects the change in conductivity in going from the conductive fabric to the open area of the wound. Detection of the edge of the wound makes the radar a very sensitive method for resolving and locating wounds. The same radar is able to easily detect a hairline scratch left by a razor in the surface of a steel plate.

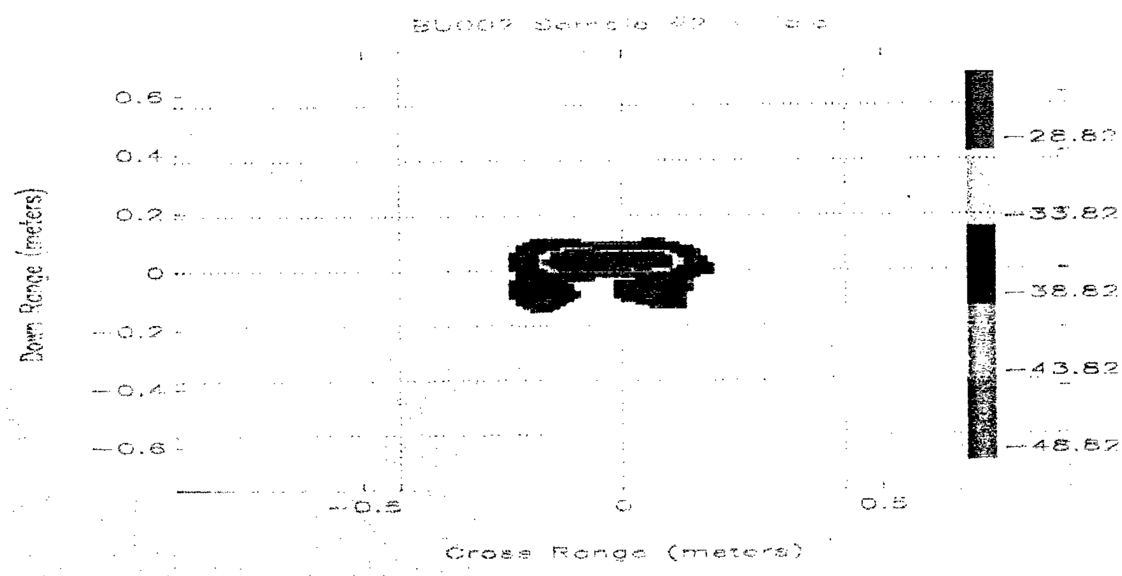
The radar was able to penetrate an outer layer of nonconductive fabric to detect a hole in an underlying piece of conductive fabric. Antistatic fabric containing electrically conductive carbon filaments (fourth entry in Table 1) was separately measured and determined not to contain enough conductor to produce a high radar return. The antistatic fabric was then placed over conductive fabric containing a hole and the underlying hole was successfully detected by the radar.

MIT Lincoln Laboratory indoor radar range was the test site for performing measurements. Radar frequencies available were 0.15-1 GHz (UHF, VHF, P); 2-18 GHz (S, C, X, K_u) and 27-36 GHz (K_a). X-band (8-12.5 GHz) was chosen as the interrogation band for the tests. The transmitted radar power was 2 watts peak with a 10 ns pulse width and a 5.735 MHz PRF (pulse repetition frequency). The measurement volume was cylindrical with a height and diameter of 6 feet. The far field of the indoor range was 25 feet; textile measurements being performed in the near field. The radar performed transmit and receive of vertical and horizontal polarizations yielding the standard four transmit/receive channels; VV, HH, HV and VH. The vertical polarization component pointed toward the ceiling and the horizontal component pointed along the floor. The radar illuminated fabric samples horizontally along the direction of the ground. Fabrics were placed on a styrofoam platform whose normal was tilted 20° off the vertical toward the radar. Fabric samples were oriented with the 12" edge facing the illuminating radar; the 12" edge being cross range and the 9" edge being down range.

The conductive fabric listed as the first entry in Table 1 (the fabric appears on the left in Figure 2) was one fabric tested and the radar measurements are shown in Figures 3 and 4. Radar images in Figures 3 and 4 were produced by the vertical transmit and vertical receive channel (VV). The upper and lower contour images of Figure 3 compare the radar return of the fabric with the hole to the radar return of the fabric without the hole. The 3D images of Figure 4 present the same data as Figure 3 only in 3D form. In Figure 3, the feature appearing at the center of the upper contour, not present in the lower contour, is the radar successfully identifying the hole in the fabric.

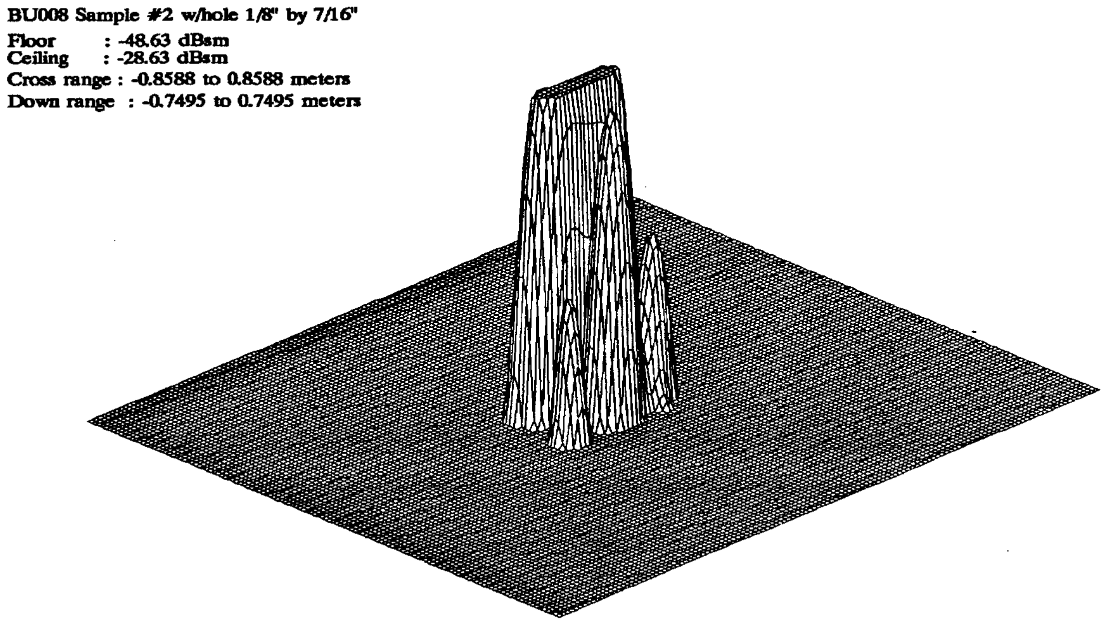


Radar return from conductive fabric with a hole

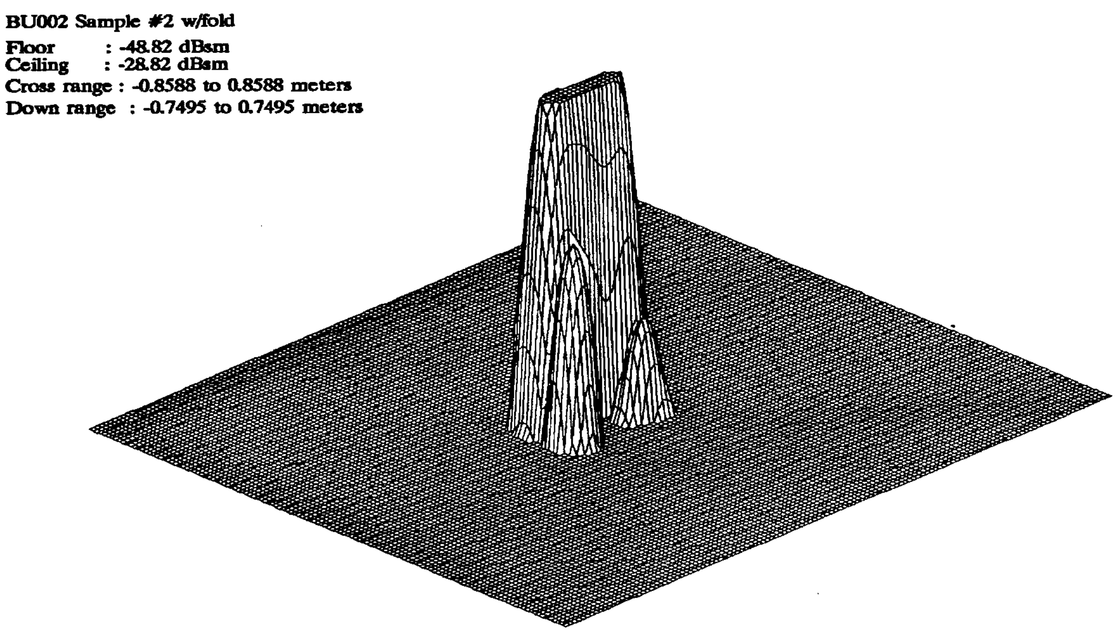


Radar return from conductive fabric without a hole

Figure 3 Comparison of contour radar returns from electrically conductive fabric with and without a small caliber sized hole at center of fabric (measurements performed at MIT Lincoln Laboratory indoor radar test range).



Radar return from conductive fabric with a hole



Radar return from conductive fabric without a hole

Figure 4 Comparison of 3D radar returns from electrically conductive fabric with and without a small caliber sized hole at center of fabric (measurements performed at MIT Lincoln Laboratory indoor radar test range).

The upper 3D plot of Figure 4 shows the hole as a central peak between two smaller peaks. Orientation of the radar and fabric in the contour images of Figure 3 can be realized by aligning the 12" edge of the fabric along the cross range axis of the contour image. The interrogation wave from the illuminating radar enters from the bottom of the image. For the 3D images of Figure 4, the cross range axis is the forward right edge, the radar entering from the bottom right.

Features appearing in the radar return, or echo, from the fabric without the hole can be understood by following the traversal of the traveling wave along the fabric. The traveling wave sweeps along the fabric, down range, from the leading edge (bottom edge of the fabric in Figure 2) and encounters the horizontal crease at the midline of the fabric. The crease produces the two separate echos appearing at midline in the radar images. The traveling wave then continues sweeping down range until it finally echos off the back edge of the fabric (top edge of the fabric in Figure 2) producing the single large feature in all of the images. The radar echo from the crease is due to a change in the fabric profile whereas the echo from the back edge is due to a change in conductivity in moving off the fabric.

Observed radar returns from the conductive fabric are produced by two effects. The dominant effect is due to the change in conductivity sensed by the radar wave moving over the edge of a hole or the edge of the fabric. The less dominant effect is due to changes in the profile of the fabric caused by creases or wrinkles. In Figure 4, the relative contribution of these two effects is evident in the 3D radar image of the fabric with a hole. The central peak and large peak behind it are due to the dominant effect of the radar wave encountering an edge on the fabric, the hole and back edge respectively. The smaller peaks on either side of the central peak are due to the less dominant effect of creases and wrinkles. The images are plotted logarithmically in dbsm (decibel square meters) so the numerical difference in peak heights is actually greater than it appears in the images.

Radar interrogation of medical smart textiles in the field will result in information about holes left by penetrating objects versus image information about creases and wrinkles which might lead to false wound identification. The large feature appearing in all the images of Figures 3 and 4 would not exist in the field because a uniform made of medical smart textile would not have edges, short of the neckline and cuffs for shirts and pants. The conductivity could be tailored to gradually decrease toward the edge, reducing the radar return from those edges. Although holes due to wounds produce the dominant radar return, the overall signal level is still affected by the wrinkled profile of the textile [2, 10, 14].

The radar cross section σ_{RCS} of a piece of wrinkled conductive fabric is expressed in

$$\sigma_{RCS} = \frac{4\pi A_{fabric}^{2} \sin^2\theta}{\lambda^2} e^{-\sigma_{wrinkles}^{2}} \qquad \textbf{Equation (2)}$$

Equation (2) where

A_{fabric} = area of the fabric
θ = tilt angle toward radar
λ = radar wavelength

This is the radar cross section of a conductive surface in the *slightly rough* approximation [2, 10]. The leading term in Equation (2) is the radar cross section of a smooth unwrinkled piece of conductive fabric and the exponential term represents the effect of wrinkles in the fabric. Wrinkles result in an overall degradation of the radar signal. The root mean square variance $\sigma_{wrinkles}$ of the wrinkle height distribution is expressed in Equation (3) as

$$\sigma_{wrinkles} = \frac{2\pi \langle h \rangle_{wrinkles} (1 + \sin\theta)}{\lambda} \qquad \textbf{Equation (3)}$$

where $\langle h \rangle_{wrinkles}$ is the root mean square height of wrinkles in the fabric.

A radar cross section of $\sigma_{RCS} \sim 1$ meter^2 for the 9" x 12" fully conductive wrinkled fabric results from characteristic values of $A_{fabric} \sim 700$ cm^2, $\theta \sim 20°$, $\lambda \sim 3$ cm (X-band) and $\langle h \rangle_{wrinkles} \sim 0.5$ cm. Neglecting degradation due to wrinkles, the radar cross section is ~8 meter^2. Wrinkles degrade the radar cross section by ~0.14, lowering it significantly to $\sigma_{RCS} \sim 1$ meter^2. This degradation is actually desirable since it enhances radar camouflage. This enhancement is achieved at no cost since wrinkles and creases inevitably form in the fabric.

3.3 Interrogation Field Radar

Electrically conductive fabrics were successfully tested at MIT Lincoln Laboratory indoor radar range against X-band (10 GHz; 3 cm) radar to prove the feasibility of remotely sensing a hole left in a fabric representative of a wound. A field system is envisioned that would operate at the longer wavelengths of S-band (3 GHz; 10 cm) due to the requirement of foliage penetration.

In the passive mode of the textile (Figure 1), a platform such as a Blackhawk UH-60 Medevac helicopter [11] (an Apache attack helicopter appears simply for illustration), is interrogating the smart textile through radar illumination. The radar must be capable of penetrating obstacles, foliage and outer layers of clothing. The penetration requirement of the radiation is the prime reason for using a radar, as opposed to visible, infrared or thermal radiation which does not possess the same ability to penetrate obstacles. The frequency (wavelength) of the radar will determine its penetration capability in addition to its ability to resolve the minimum wound size registered in the smart textile [21, 22]. The effects of penetration and small wound resolution compete against one another. A longer wavelength radar would be best suited to penetrate an obstacle such as foliage whereas a shorter wavelength radar would be best suited to resolve small wounds. An S-band radar has been chosen as the compromise to satisfying both constraints simultaneously.

The passive smart textile will be interrogated by a radar which must transmit enough power to produce a detectable return from the textile. An estimate for the ratio of received to transmitted power, using the radar range equation [21, 22], yields 10^{-6} (-60 decibels). This ratio assumes a physical object size of ~1 meter^2, range to target of ~1 kilometer, transmitter beam width of ~2° and S-band radar wavelength of ~10 centimeters (~3 GHz). The physical object illuminated by the radar is the dismounted soldier wearing medical smart textile.

Radio-Research Instrument Co., Inc. supplies an S-band search radar that satisfies the requirements for passive textile interrogation. A pulsed versus CW (continuous wave) radar is preferred which supplies differential range data that will assist the interrogation of the textile in different orientations. Characteristics of the S-band radar are; frequency - 3.025 GHz; range - 0.5-48 miles; output power - 50 kW; pulse width - 75 ns; PRF - 4 kHz and; input power - 220 V, 60 Hz.

Radar wound resolution depends upon aperture size as well as radar frequency. For a moving platform, such as the helicopter in Figure 1, a SAR (synthetic aperture radar) technique [6, 22] can be employed to obtain better size resolution at the textile. The moving radar forms a synthetic aperture that is larger than the stationary aperture. The larger size of the synthetic aperture yields higher resolution data which can be post processed to yield smaller wound information. In cases where the radar platform is stationary, a separated shared aperture can be employed to increase resolution.

The ability of a radar to penetrate foliage depends upon bandwidth as well as frequency. Narrow bandwidth transmitters are easily decorrelated by clutter sources [15], such a foliage, making penetration difficult. Ultra-wideband SAR's [7, 23,] have been successfully demonstrated to penetrate foliage while retaining resolution size.

3.4 Surgical Operating Environment of the Future

Northrop Grumman Corporation is exploring remote information transfer of physiological data in the Surgical Operating Environment of the Future (OEF). SME smart medical textile is being considered as the sensor net array that would sense and transmit physiological data. A surgical table outfitted with smart textile sensors would allow for the continuous monitoring of vital signs that could be remotely transferred to a surgical command center. A preliminary design of the table from Northrop Grumman Corporation with specifications regarding sensing of desired physiological signs will be necessary to design smart textile for the OEF. Northrop Grumman has considered remote transfer of data by infrared. The smart textile would be a conductive sheet of fabric containing physiological sensors that send information to IR transmitters for remote transfer. Smart textile could also be used as a Faraday shield to protect the OEF from extraneous electromagnetic interference.

Medical smart textiles were initially conceived by SME to gather open wound information at trauma sites. The Phase I effort addressed design of the textile for this purpose. Smart textile interrogation sensed simultaneously with vital signs at trauma sites would provide more accurate wound information and prevent the false identification of wounds. In a military engagement, bodily functions that might be sensed along with smart textile interrogation in the field are sweating, urination, defecation and, of course, bleeding. Of these bodily functions, military doctors chose to sense bleeding. Blood is composed mainly of water. The passive mode of the textile is interrogated by a radar which is differentially sensitive to absorption by water. The active mode of the textile is a resistor network etched into a conductive fabric that would register changes in resistivity due to blood solids.

3.5 Summary of SME Phase I Design Specifications

SME Phase I deliverables are design specifications for a medical smart textile along with system parameters for an interrogation radar comprising the passive mode of the wound

identification system. The SME Phase I effort progressed beyond planned goals resulting in candidate fabrics for the medical smart textile and radar measurements of those fabrics.

SME Phase I design specifications follow:

- Electrically conductive fabric is the substrate for both active and passive SME medical smart textile. Fabric weight is ~1-4 oz/yd^2; fabric conductivity can be varied from 0-100%; fabric content is conductive and conventional yarns.

- Active, wear-and-activate, medical smart textile possesses a cross hatched network of conducting paths etched into conductive fabric for wound identification. Conductive paths should not exceed a few millimeters in width or separation for reasonable wound resolution.

- Passive, wear-and-forget, medical smart textile is the same fabric as the active textile. Passive textile appears uniformly conductive to an S-band interrogation radar that is incapable of resolving the conductor network in the fabric.

- An S-band search radar will interrogate the passive medical smart textile for open wounds. Radar characteristics are: frequency - 3 GHz; range - 1 km; beam width - 2°; maximum output power - 50 kW; pulse width - 75 ns; PRF - 4 kHz; input power - 220 V, 60 Hz.

4. Feasibility of SME Phase I Approach

The SME Phase I approach to gathering open wound information utilizes a predesigned, wearable medical smart textile that can be interrogated for open wound information. The SME approach has been demonstrated to be feasible. Measurements performed at MIT Lincoln Laboratory indoor radar range demonstrated the feasibility of open wound identification by a radar. A benefit of the approach is the use of existing fabrics that have been *marginally* modified to sense open wound information. Existing fabrics with marginal modifications will retain the many desirable fabric properties that have already been engineered into them. The SME approach is feasible both technically and developmentally.

5. SME Phase II Topics

Design specifications resulting from the SME Phase I effort will be used in the SME Phase II effort to construct a demonstration prototype of a medical smart textile that can be sensed for open wound information.

6. Literature References

[1] American Conference of Government Industrial Hygienists (ACGIH), *1996 TLVs and BEIs; Threshold Limit Values for Chemical Substances and Physical Agents; Biological Exposure Indices*, Second Printing, ACGIH, Cincinnati, OH (1996)

[2] Beckmann, P. and Spizzichino, A., *The Scattering of Electromagnetic Waves from Rough Surfaces*, Macmillian Co., Pergamon Press (1963)

[3] Cameron, R. M.; Stryker, T.; Mitchel, D. L. and Halliday, W. S., *Development and Application of Airborne Ground-Penetrating Radar for Environmental Disciplines*, SPIE Vol. 1942, 21-33 (1993)

[4] Clement, D. and Watkins, W. R., Chair/Editor, *Characterization, Propagation, and Simulation of Sources and Backgrounds II*, SPIE Proceed. Vol. 1687, Session 5, *Camouflage and Clutter* (1992)

[5] Conant, J. B., Chairman, *Visibility Studies and Some Applications in the Field of Camouflage*, Summary Technical Report of Division 16, NDRC, Vol. 2 (1946)

[6] Drabowitch, S. and Ancona, C., *Antennas*, Vol. 2: Applications, Hemisphere Pub. Corp. (1988)

[7] Fleischman, J.; Toups, M. F. and Ayasli, S., *Summary of Results from a Foliage Penetration Experiment with a Three-Frequency Polarimetric SAR*, SPIE Vol. 1693, Surveillance Technologies II, 151-160 (1992)

[8] Giglio, D.; Ralston, J. and Braunstein, M., *Perspective on Underground and Obscured Target Detection and Imaging*, SPIE Vol. 1942, 2-11 (1993)

[9] Headquarters, Department of the Army, Field Manual No. 7-8, *The Infantry Platoon and Squad (Infantry, Airborne, Air Assault, Ranger)* (31 Dec 1980)

[10] Ishimaru, A., *Wave Propagation and Scattering in Random Media*, Vols. 1 & 2, Academic Press (1978)

[11] Lambert, M., Editor-In -Chief, *Jane's All the Worlds Aircraft*, 1993-94, Eighty-Fourth Year Issue, Jane's Information Group, Inc., Alexandria, VA (1993)

[12] MacKeen, P. C.; Person, S.; Warner, S. C.; Snipes, W. and Stevens, S. E. Jr., *Silver-Coated Nylon Fiber as an Antibacterial Agent*, Antimicrobial Agents and Chemotherapy, Vol. 31, No. 1, 93-99 (1987)

[13] Massachusetts Department of Public Health, Document 105 CMR, *Radio Frequency Exposure Limits for Public Exposures*

[14] Nicodemus, F. E., *Directional Reflectance and Emissivity of an Opaque Surface*, Appl. Opt. Vol. 4, No. 7, 767-773 (1965)

[15] Perina, J., *Coherence of Light*, Reidel (1985)

[16] Ramsley, A. O., *Camouflage Patterns - Effects of Size & Color*, Tech. Report Natick/TR-79/030 (1979)

[17] Ramsley, A. O., *Selection of Standard Colors for the Woodland Camouflage Pattern*, Tech. Report Natick /TR-81/030 (1981)

[18] Ruck, G. T., Barrick, D. E., Stuart, W. D., Krichbaum, C. K., *Radar Cross Section Handbook*, Vols. 1 & 2, Plenum (1970)

[19] Schultz; F. V.; Burgener, R. C. and King, S., *Measurement of the Radar Cross Section of a Man*, Proceedings of IRE (IEEE), 476-481 (Feb 1958)

[20] Sheen, D. R.; Lewis, T. B.; Wei, S. C. and Kletzli, D., *Imaging of Buried and Foliage-Obscured Objects with an Ultrawide Bandwidth Polarimetric SAR*, SPIE Vol. 1942, 12-20 (1993)

[21] Skolnik, M. I., *Introduction to Radars Systems*, McGraw-Hill Book Company (1962)

[22] Skolnik, M. I., Editor-in-Chief, *Radar Handbook*, McGraw-Hill Book Company (1970)

[23] Toups, M. F. and Ayasli, S., *Results From the Maine 1992 Foliage Penetration Experiment*, SPIE Vol. 1942, 66-75 (1993)

[24] Zajtchuk; COL R.; Jenkins; D. C.; Bellamy, COL R. F. and Quick, C. M., Editors, *Textbook of Military Medicine, Part I: Warfare, Weaponry and the Casualty, Vol. 5: Conventional Warfare:, Ballistic, Blast and Burn Injuries*, published by Office of the Surgeon General at TMM Publications, Walter Reed Army Medical Center, Wash. D.C. (1990)

[25] 1990-1991 Annual Report, Maryland Institute for Emergency Medical Services Systems, Maryland Trauma Centers Statistics